LAUNCHING TRAFFIC CAMERAS INTO SPACE

Livermore researchers are developing traffic cameras to augment their efforts to improve space-debris collision predictions.

Artist's concept courtesy of National Aeronautics and Space Administration (NASA).

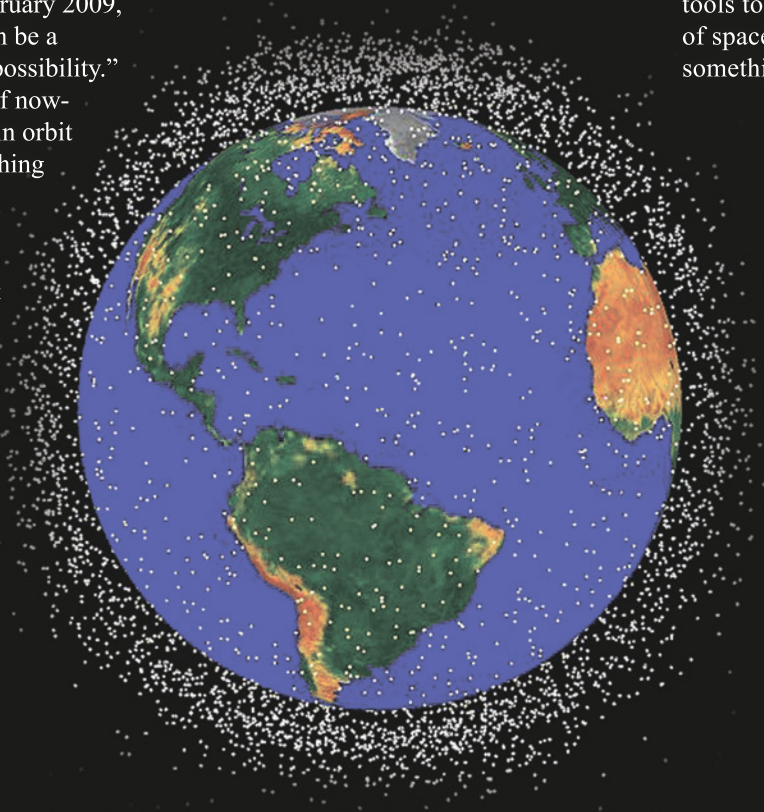
SINCE the Soviet Union launched the world's first artificial satellite, Sputnik I, in 1957, thousands of satellites have been sent into space to orbit Earth. Today, nearly a thousand active satellites are in orbit. The bulk of them are used for invaluable services, such as critical military and intelligence data collection, global positioning systems (GPSs), telecommunications, navigation systems, and weather and climate monitoring. These satellites are increasingly at risk of colliding with damaging space debris. Livermore engineer and lead systems developer Vincent Riot says, "Following the collision between an American Iridium communication satellite and a defunct Russian Cosmos satellite in February 2009, we now know that collisions can be a reality and not just a statistical possibility."

Space waste, the collection of now-useless, human-created objects in orbit around Earth, consists of everything from spent rocket stages and defunct satellites to collision fragments and lost astronaut tools. Space objects do not orbit in a perfect vacuum. Small amounts of gas from Earth's atmosphere extend far into space and act to slow down the motion of satellites through drag. Because the frictional forces are so small, a great number of useless objects remain in orbit.

Each type of space hardware is best suited to a particular orbital regime, or region. For example, low-Earth orbit—160 to 2,000 kilometers above Earth's surface—contains a higher proportion of space stations, upper rocket stages, and amateur satellites. In middle-Earth orbit, 2,000 to 35,876 kilometers in altitude, navigation satellites are positioned. Telecommunications satellites are sent to geostationary orbit, located at 36,000 kilometers. Current guidelines require that satellites either de-orbit or boost their orbits to a higher "graveyard orbit" within 25 years after the end of their service life.

Critical density occurs when new debris is created faster than frictional forces can remove these objects from orbit. In the last 20 to 30 years, only a handful of collisions have occurred between tracked objects, such as satellites and larger debris. Now, as regions of space become more crowded, the threat of collision is expected to rise. Eventually, some regions of space could become too crowded for future launches.

Physicist Willem De Vries of the Physical and Life Sciences Directorate says, "When we were designing a set of analysis, simulation, and visualization tools to improve situational awareness of space objects, we asked: Is there something we can do to prevent satellite



This NASA computer-generated debris plot depicts the number of tracked objects in low-Earth orbit alone. Approximately 95 percent of the objects in this illustration are debris. Low-Earth orbit is within 2,000 kilometers of Earth's surface and is the most concentrated region for orbital debris.

collisions with damaging space debris?" (See *S&TR*, July/August 2009, pp. 4–11.) "We considered using nanosatellites, an emerging technology that is transitioning from a university-oriented experimental platform to being seriously considered for operational use."

Cube Satellites Monitor Space Junk

One type of nanosatellite (defined as an artificial satellite with a launch mass between 1 and 10 kilograms, or 2.2 and 22 pounds) is the "cube satellite." CubeSats, as they are nicknamed, measure 10 centimeters on a side, just a bit larger than a Rubik's cube. A pair of three-unit CubeSats (called 3U CubeSats) equipped with optical imaging payloads will demonstrate the main elements of the Space-Based Telescopes for Actionable Refinement of Ephemeris (STARE) concept.

During launch, large satellites require ballast to balance the spacecraft. By taking the place of ballast dead weight, CubeSats can ride along as auxiliary payload, making them fairly inexpensive to launch. However, CubeSat developers must show that their satellite adheres to a strict set of engineering standards, so as not to jeopardize the primary launch payload.

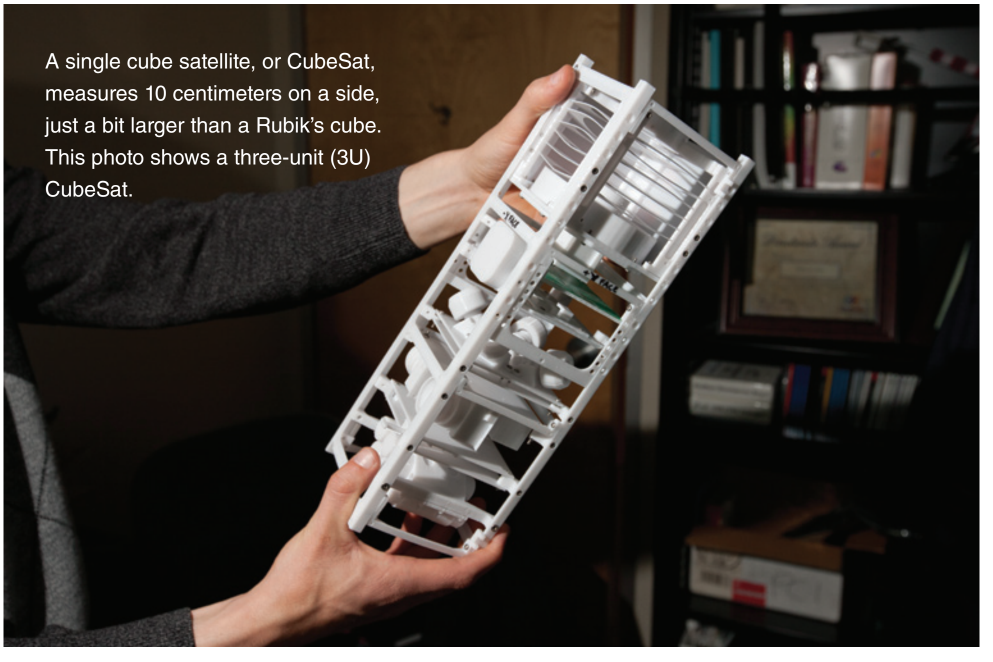
In the first phase of the STARE project, software tools are being developed for enabling operators to predict collisions with high accuracy, using the improved positional information that nanosatellites will provide. Later this year, in the proof-of-concept phase, the Livermore-developed technology that makes use of these common small satellites will be launched into space. The Laboratory's idea could be described as using traffic cameras in orbit to track space objects. A multidisciplinary team of physicists and engineers at Livermore developed the STARE project with funding from Livermore's Laboratory Directed Research and Development Program.

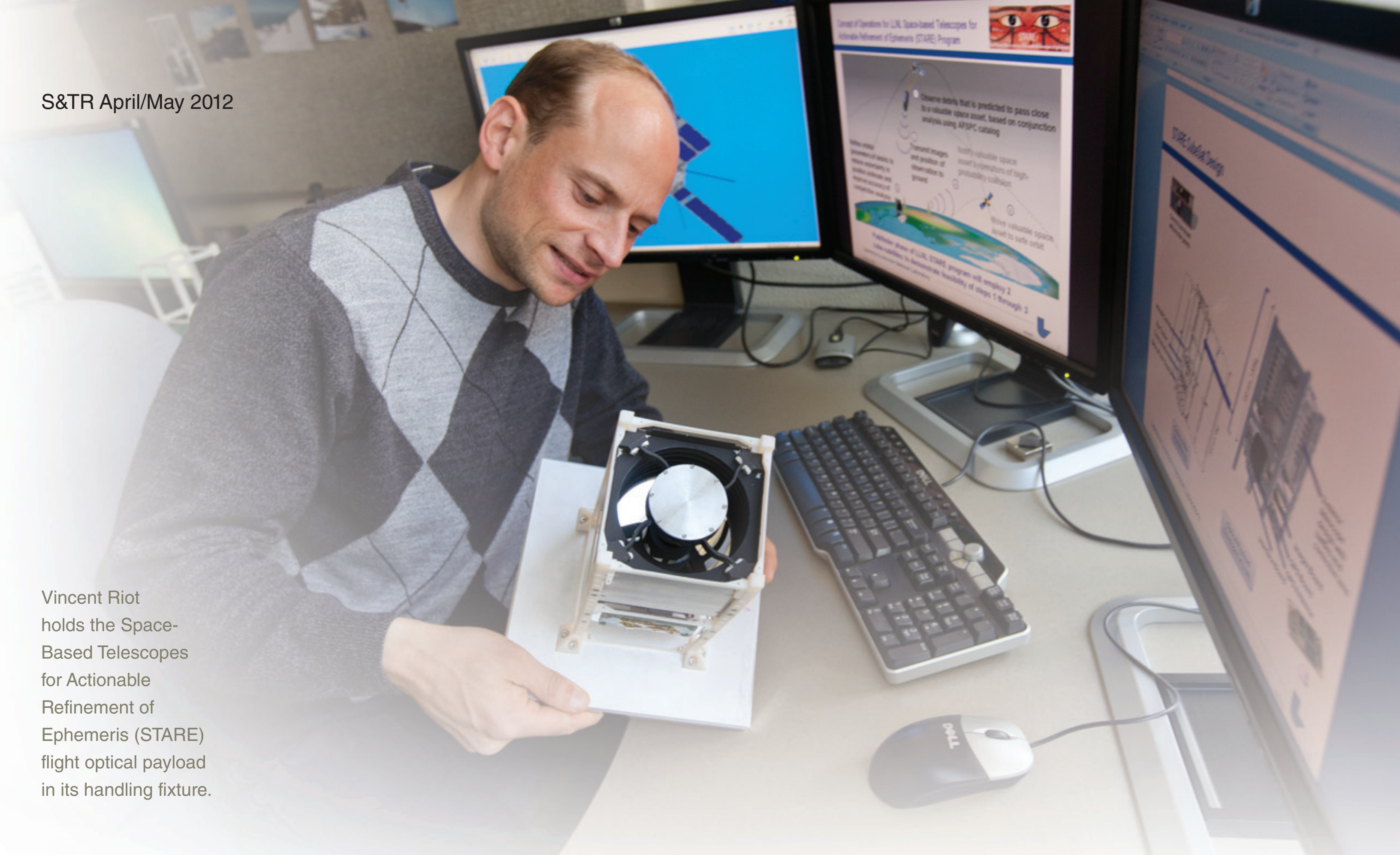
The STARE project is the story of an extraordinary partnership. To develop this new technology, Livermore established a multi-institution joint venture between Boeing, an aerospace company with a history of bringing satellite products to market; Texas A&M University and the Naval Postgraduate School, two academic institutions with research expertise in this area; and the National Reconnaissance Office, the federal sponsor of the first-mission CubeSats. The partnership relies on the strength of the Laboratory to demonstrate the proof of concept and produce a functional prototype.

Faster Than a Speeding Bullet

Space debris more or less maintains the orbit of its parent satellite. If a satellite was launched in low-Earth orbit, for example, any remaining debris will stay in this orbit, overlapping the trajectories of newer objects. Debris is a potential collision risk to active spacecraft; a piece as small as a marble can shatter a satellite. "Orbital speeds are about 7 kilometers per second, more than 10 times the speed of a bullet," De Vries says. In the last two decades, five satellites have been disabled by collisions with large debris.

The majority of the estimated tens of millions of pieces of space debris are small particles—dust from solid rocket motors and paint flakes that come loose from spacecraft surfaces, for example. The impact of these particles causes erosive damage, similar to sandblasting. The National Aeronautics and Space Administration's Debris Office estimates that as many as 300,000 objects larger than 1 centimeter are present in low-Earth orbit alone. A much smaller number of the debris objects are larger, more than 10 centimeters. The only protection against this larger debris is to maneuver the spacecraft to avoid a collision. If a collision with larger debris does occur, many of the resulting fragments from the damaged spacecraft will be the size of a softball or larger, and these objects pose a greater risk of damage from a collision. The 2009 collision between the Russian and American satellites over northern


A single cube satellite, or CubeSat, measures 10 centimeters on a side, just a bit larger than a Rubik's cube. This photo shows a three-unit (3U) CubeSat.



Vincent Riot holds the Space-Based Telescopes for Actionable Refinement of Ephemeris (STARE) flight optical payload in its handling fixture.

Siberia produced a few thousand pieces of debris, still in orbit.

Removing defunct satellites is problematic. In 2007, China performed an antisatellite weapons test at almost 805 kilometers in altitude, destroying an aging weather-satellite target using a kill vehicle launched on board a ballistic missile. The result was 2,000 baseball-sized or larger pieces of junk that could cripple a satellite on impact and over 2 million pieces that could cause damage.

Space Base

At the start of the STARE project in May 2010, De Vries conducted an extensive conceptual study to determine whether monitoring the path of debris from space—as opposed to current ground-based monitoring—would be feasible and provide better results. “To observe space objects from the ground, the ground area must be dark, while the objects must be illuminated by the Sun. This requirement limits the debris-observation window to between 1 and 2 hours after sunset and before sunrise,” De Vries says. Inclement weather further limits observation. “To see all the debris in a short period of time, about 48 ground stations around the world would be required, which would be expensive,” he says. “However, satellites outside Earth’s atmosphere orbit quickly, and space is always dark, providing multiple times to observe objects within a single day.” The study included information on where to locate the CubeSats, how well they would work, and how many would be needed to provide valuable data.

The study concluded it would be easier and more efficient for satellites to obtain the needed observational images and data from space. A day’s worth of data would give researchers better information regarding the orbit of debris and allow them to determine how close the debris might come to a satellite in its path. Only the orbits of objects that would come close to satellites within a couple of days would be refined with the knowledge gleaned from the observational data. Predictions cannot be made weeks in advance because orbits are not completely stable. “When the Sun flares, for example, the atmosphere puffs up, and creates drag that changes orbits,” says De Vries.

Actionable Data

The U.S. Joint Space Operations Center (JSpOC) gathers ground-based observations of space debris. The primary source of the data is the Space Surveillance Network, a global network of 29 optical telescopes and radars operated by the U.S. Air Force. The Space Surveillance Network follows more than 20,000 manmade objects in orbit as big as a baseball or larger, each capable of destroying satellites.

Every day, JSpOC screens a list of satellites. The objects with the highest priority are human-related spacecraft, such as the International Space Station, followed by military and intelligence satellites. One sensor tracking an object in orbit and determining its position at a moment in time is called an observation.

Multiple observations strung together in the same pass as the satellite flies overhead are called a track. JSpOC determines how many tracks of data are nominally required to determine each object's orbit based primarily on the object's type and size and the change rate of its orbit.

These requirements are then fed into an algorithm along with the sensor availability. The algorithm assigns satellites to sensors in the network. During the next day, the sensors track their assigned satellites and transmit the data back to JSpOC. The data are then used to calculate a satellite's location and its predicted position forward and backward in time. The entire process is repeated daily.

Because JSpOC tracks space objects, it can warn satellite operators when they may need to maneuver their satellites to prevent a collision with another space object. However, the level of positional accuracy for the complete set of tracked space objects is insufficient to predict collisions with an adequate degree of certainty. "Operators receive warnings if an object and a satellite are close, but the prediction may be accurate to within only a kilometer or so, which is not accurate enough," De Vries says. Large operations, such as the Iridium constellation, a group of 90 satellites providing voice and data coverage to phones, pagers, and integrated transceivers, would receive warnings to move 10 satellites per day at that accuracy level. Satellites cannot move repeatedly because they have limited fuel to maintain their orbits during their 5- to 10-year lifetimes. Once they use up their fuel, they become uncontrollable.

"Operators know that 9,999 of 10,000 warnings will be false alarms, so most are ignored," says De Vries. "With the STARE project, we intend to refine this by a factor of 100. So, instead of 1 in 10,000 warnings being accurate, 1 in 100 is accurate. Warning rates would be reduced to once per the lifetime of a satellite."

The STARE project will use the Boeing-built Colony II bus developed under a contract with the National Reconnaissance Office. "A Colony II bus is a nanosatellite containing a radio, batteries, attitude control unit, solar panels, and other parts with an empty space inside, roughly half the volume," explains Riot, who coordinated the effort. A payload can be inserted into this space to accomplish something useful, such as STARE's miniature telescope with GPS tagging. "Think of Boeing's Colony II bus as a carriage with wheels, suspension, steering, and a frame," says Riot. "The carriage performs the basic capabilities of driving around and turning. Our creation, the payload, is placed on the carriage to deliver images of orbital debris."

Refinement of Ephemeris

"We need to know the position of observed satellites or pieces of debris we're targeting at a given time," says Physical and Life Sciences postdoctoral

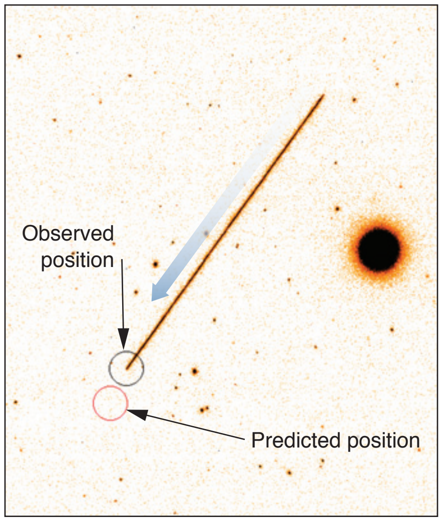
This 3U CubeSat contains the Livermore-developed optical payload. The unit will ride along as auxiliary payload when launched later in 2012.

scholar Lance Simms. "When we take a picture, we get the object's location in our camera's pixel frame. But we still have to map that information to the celestial frame of the stars. To accurately locate satellites, we need to measure the positions of the stars in the image and the start and end position of the debris track to subpixel accuracy." Timing is important because multiple frames are required at the time the observed satellite is expected to arrive and because the exact times of the exposures are used to refine the orbit parameters.

Another camera will take pictures of the sky and compare those to the star catalog onboard to find the best match. Because the positions of the stars are known, the 3U CubeSat uses these data to report its coordinates and which way it's pointing with respect to the Sun or Earth. Then researchers can calculate how much the satellite needs to rotate to look at a certain part of the sky. Because objects in space cannot push themselves, the 3U CubeSat uses wheels that rotate in one direction and cause the bus to move the other way. Many external forces, such as solar winds, will hit the unit, so it must keep controlling its position and taking images of its location.

The 3U CubeSat is tasked with acquiring observations of objects for 24 hours. These data are then processed and aggregated to improve the orbital parameters. Once the uncertainty has been reduced, the data are used to update the forecast to the closest approach between satellites and debris and the probability of collision.

"Making sure we could successfully capture images with a camera within a CubeSat was the main constraint," Riot says. That small space also has to contain an attitude control system, a radio system to send data, a power system consisting of batteries and solar panels, and a GPS. "Attitude control is the most complicated part of the system," he says. "We need to know where the 3U CubeSat is and have a way of rotating it so it points at a star field without drifting."



This image taken in Livermore November 22, 2011, depicts the start and end positions of India's Polar Satellite Launch Vehicle Rocket Body tracked to subpixel accuracy. The path is captured by the camera's pixel frame and then mapped to the celestial frame of the stars (dots).

Tiny Telescopes

Optical engineer Brian Bauman and mechanical technician Darrell Carter designed and fabricated the optical payload, which includes the telescope and camera. The team chose to use Boeing's star-tracker camera because the Colony II bus already supports the device. In the images captured by the camera, stars appear as dots, and the nanosatellite uses them to calibrate where to point. (See the figure above.) When pieces of debris drift through the field of view, they look like streaks or lines. Images—one set of frames per orbit—are stored until the 3U CubeSat passes over the ground stations.

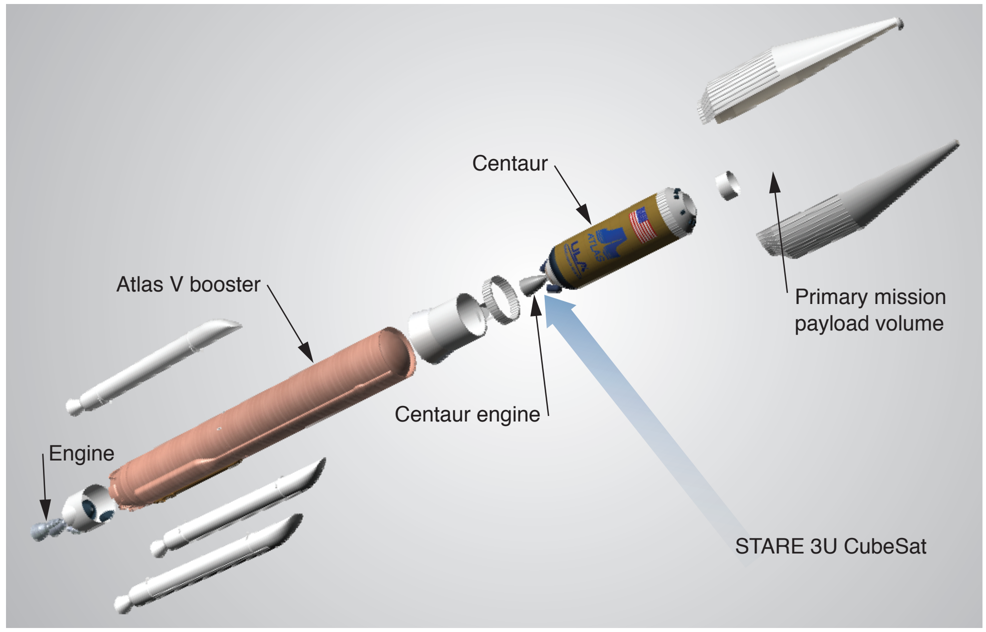
Says Riot, "Once the Colony II bus is launched, it's autonomous, circling Earth every 90 minutes, or 15 times per day. It sends data collected from objects once a day. The unit even preprocesses images so they don't have to be downloaded, an important advantage considering the limited data rate available."

The field of view must be wide enough for researchers to see the entire streak with both end points to determine the orbital path of the debris. "Shapes become elongated at the edges of the view, appearing as teardrops rather than round dots," Bauman says. "Because of the short timeline, an initial two-mirror telescope was built. A soon-to-be-built unit will include lenses that correct for the curved focal plane and other aberrations, making the shapes more distinct. An important aspect of the telescope's viability relies on using modern manufacturing techniques to reduce costs."

Once the Livermore telescope leaves the lab, new challenges begin. "CubeSats have never held optical telescopes requiring precision alignment," Bauman says. "It's a very tall order. Our 3U CubeSat will be located near the engine during launch and will experience a high level of vibration, which is a concern because very small changes in the distance between the two mirrors will produce out-of-focus images. In optical design, the challenge is often in the constraints." As images come in from the mission, researchers will learn how to improve future designs. "We'll need to tweak the design," says Bauman. "Recently, I've been inspired by cell-phone camera configurations, which use only one mirror but bounce light off that mirror many times."

Simms began work on the project by developing the algorithm that detects the debris tracks from end point to end point, one unlike any other he had seen in research. "Finding stars is common in astronomy," says Simms. "However, in that field, researchers are not really concerned with finding the track end points. We need to be able to find the streak end points to a precise level. If we were using a perfect camera and set of optics, we could capture

The STARE CubeSats are integrated into the main box that bolts to the launch vehicle.



This artist's rendering shows where the STARE 3U CubeSat will be positioned on the launch vehicle, an Atlas V rocket.

a perfect line with perfect ends. In reality, the telescope causes the image to blur. Within that blur is the real end point." The team does not want to send all the data back to Earth because it would become expensive in terms of time and resources. "Our idea is to perform all the processing on the satellite and send down only the stars' locations and the tracking points," says Simms. "These data are all we need to refine the orbit of the satellite or piece of debris."

Simms also wrote the firmware code for the payload. "We have a small microprocessor in the payload of the 3U CubeSat that talks to the larger processor on the Colony II bus," says Simms. "The vehicle performs attitude control and points at the stars, and the payload is strictly responsible for taking the pictures and processing them." He wrote the entire code that runs the payload processor; acquires the GPS location, time, and images; and runs the satellite algorithm on the images. The processor returns the information to the vehicle, which sends it to the ground.

The code took a year to write and to ensure it is error free and responds to all commands. At the Naval Postgraduate School, the team ran the processor through a battery of tests and found no obvious bugs. "We've also taken the processor out at night and pointed at the stars," says Simms. "It has successfully sent back images and coordinates."

While the researchers wait for the STARE 3U CubeSat to launch into low-Earth orbit on an Atlas V rocket, they will refine their algorithms and develop software to automate data capture and delivery. These data will tell the team how well CubeSats on the Colony II buses are doing. "Our main concern is jitter from noise in the satellite attitude system," says De Vries. Once it's launched, the researchers will also get telemetry data—voltages, currents, energy uses—from the Boeing vehicle. The lifetime expectancy of the 3U CubeSat is nominally one year. Many of the parts are not particularly sophisticated, such as the radio and the sensor, which Boeing uses because they are space-qualified. Next-generation STARE satellites will feature an improved cooled imaging sensor to enable observations at longer ranges.

Constellation of Possibilities

If the initial mission is successful, Livermore could begin building nanosatellites for various applications, such as space weather and other scientific missions. Eventually, the Laboratory could develop a full constellation of nanosatellites proposed as a later phase of STARE. For an 18-nanosatellite constellation, STARE has the capability to reduce the collision false-alarm rate by 99 percent, up to 48 hours ahead of the closest approach, which would be attractive to satellite owners or providers.

The team will be looking for sponsors for the constellation. "While typical single satellites cost several hundred million dollars to one billion dollars, a full constellation of 18 nanosatellites to track space debris costs only a fraction of that— about $30 million," Riot says. The constellation may prove a good candidate for technology transfer.

—Kris Fury

Key Words: nanosatellite, optical payload, satellite, Space-Based Telescopes for Actionable Refinement of Ephemeris (STARE), space debris, telescope, three-unit cube satellite (3U CubeSat), track-detection algorithm.

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